Ground Penetrating Radar: An Effective Tool for Locating Dry Caves Along a Portion of State Route 69 Near Mayer, Yavapai County, Arizona.*

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Abstract

The geophysical techniques employed for this investigation are directly applicable to the identification of shallow subsurface voids such as abandoned underground mines beneath highways.

Widening and realignment of State Route 69 traverses an area of Tertiary-age travertine bedrock near Mayer, Arizona (Figure 1). During the design phase of the project, subsurface exploration encountered small voids within the right-of-way. A moderate-size cave structure in the area was mapped by local speleologists. Arizona Department of Transportation (ADOT) was concerned that cave structures of unknown size might be found within a few feet of the new roadway subgrade. As a result, highway construction specifications contained special provisions requiring geophysical surveys to identify cave structures that could adversely affect the roadway and expose the structures that could adversely affect the roadway and expose the traveling public to possible subgrade failure hazards. ADOT's concern was realized during construction when a D-9 Caterpillar tractor broke through a cave roof and dropped about six feet into the void.

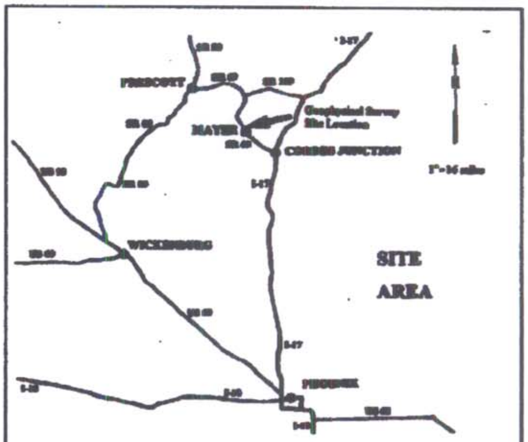

Figure 1 Project area location map

Geological Consultants Inc. of Phoenix, Arizona was contacted by C.S. McCrossan, the general contractor to conduct the geophysical surveys of the cave-affected alignment. The investigation area included both the north and south bound lanes, shoulders and median along an 800-foot section of the alignment. Ground penetrating radar (GPR) was the geophysical technique of choice because it has the highest spatial resolving capability of any geophysical method, and the data can be quickly collected and interpreted. More than 6,800 GPR measurements were collected using a Sensors & Software pulseEKKO model 100 system with a 100-MHz antenna.

One-hundred-thirty cave-type anomalies were identified from the raw GPR data along the alignment section. More than 460 anomalies were successfully interpreted from the computer processed GPR data within an interval that extended from the roadway subgrade to at least 40 feet below subgrade elevation. Air-track test drilling of suspect anomalies was used to confirm the anomalies and to refine the cave structure dimensions ranging from 2 feet in diameter to more than 40 feet in diameter. The success ratio of confirmed voids to anomalies was about 70 percent.

Recommendations were provided to ADOT, and the contractor, to remediate the cave-affected highway section. The selected remediation method was to eliminate major voids within 20 feet of the roadway subgrade using a process of (1) removing (or collapsing) the cave roof by blasting and backfilling the opening with structural fill or (2) grouting the voids full. The collapse technique was employed where large (greater than 10 feet in diameter) caves were found. Grout was used to fill smaller voids. Although deeper cave structures were present, only the upper 20 feet was remediated to effectively bridge the deeper voids while providing long-term stability of State Route 69. Survey monuments were established for monitoring roadway performance and potential settlement.

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The application of an indirect geophysical method, such as ground penetration radar surveys, and a thorough understanding of the local geological conditions, provides for a rapid, economical, focused subsurface exploration program. This type of program can be used successfully to find caves (or other underground structures) with a highway right-of-way. The data can then be used to develop cost effective mitigation measures to remediate potential hazards during project construction.

Background

Location

The cave-affected section of State Route 69 is located in the vicinity of Milepost 271 about one mile north of Mayer, Arizona, or about 75 mile north of Phoenix, Arizona. The study area is situated in the central part of the Arizona Transition Zone, a structurally distinct northwest-southeast trending zone that separates the Colorado Plateau Province to the north and the Basin and Range Physiographic Province to the south. The Transition Zone contains many of the topographic attributes of the bounding provinces: deeply incised canyons, high peaks, tablelands and mesas, broad valleys, and low mountains (Pierce, 1985).

Highway Corridor

Several years prior to the start of design studies to widen SR 69 in the project area, ADOT was aware of unusual runoff conditions in the drainage ditch adjacent to the south bound lane within a cut section of the existing highway. Following intense rainfall events, runoff flowed toward the center of the cut section and drained into a small opening at the toe of the cut. Subsequent research by the ADOT Geotechnical Section revealed that local cavers (or speleologists) knew of an accessible cave in the area. Supported by ADOT, two Prescott area speleologists mapped a small cave system, referred to as the "Mayer Mystery Cave" in 1993. Results of the mapping showed the cave extended to depths from the entrance ranging from 20 to 40 feet below the surface with connected rooms and corridors totaling a few hundred feet in length. The entire cave was within the existing highway right-of-way.

In the early 1990's, design studies were initiated to complete a 4-lane divided highway to replace the existing 3-lane segment of State Route 69. Site-specific alignment investigations were initiated along the Big Bug Creek section near Mayer, Arizona in 1993. The preliminary geotechnical investigation for the SR 69 realignment was completed in mid-1993. Small voids and loss of drilling fluid is documented in the investigation drill hole logs. ADOT attempted to characterize suspect cave features in the new alignment area in 1995 using GPR, but penetration and resolution was extremely limited by the thickness of clayey overburden soils above proposed subgrade elevation. ADOT deferred further investigations until construction of the cave-affected alignment section had been excavated to remove overburden to near grade.

During excavation of the south bound lanes and shoulder in 1996, a D-9 Caterpillar tractor was using is single-shank ripper to breakout strongly cemented breccia and travertine limestone bedrock that had been previously fragmented by blasting. Without warning, the D-9 broke through the ground surface and dropped about 6 feet into an open void (Figure 2).

During construction, Geological Consultants Inc. was contracted to conduct ground penetrating radar (GPR) geophysical survey along the new alignment section of SR 69, north of Big Bug Bridge, near Mayer, Arizona. Specifically, the surveys were located along the southbound lanes between stations 3698+00 and 3706+00 and along the northbound lanes between stations 3697+50 to 3706+00. The median and shoulder areas were also surveyed. The geophysical data and findings were used to identify voids or caves in close proximity (within 30 feet) to the roadway grade. Large voids identified within this zone exhibit the potential to collapse under traffic-induced loads.

Highway Geology

Overview

The project area is located in the central part of the Arizona Transition Zone containing deeply incised canyons, high peaks, tablelands and mesas, broad valleys, and low mountains (Pierce, 1985). These features have been formed as a result of several episodes of crustal deformation thus creating complex geologic structures including fault bounded basins and uplifted mountain massifs. The rocks of the Transition Zone consist of Pre-Cambrian age crystalline granitic and metamorphic rocks, Paleozoic through Cenozoic age sedimentary units, and substantial accumulations of Cenozoic volcanic rocks (Geological Consultants, 1992).

Following a series of complex mid-Tertiary episodes of volcanism and deformation, the basins of central Arizona (including the Mayer, Arizona area) were loci for the accumulation of extensive deposits of clastic and basaltic rocks. Thick deposits of lacustrine limestone and spring-related travertine carbonates (limestones) were deposited during extended periods of interior drainage (Thompson, 1983).

Cave-Affected Alignment Geology

The geophysical survey was conducted in an area locally referred to as the "onyx pit". The 'onyx' is a Tertiary age banded travertine that outcrops north of Mayer in the vicinity of milepost 270, along State Route 69. The travertine is interbedded with marl, calcareous sandstone, and breccia. Significant voids are found throughout the travertine unit. The travertine is locally underlain by a very hard, well cemented breccia Prior to excavation of the roadway area, drill hole logs (ADOT, 1994 and AGRA, 1993) reported that the travertine was overlain by the residual soil and poorly to moderately cemented breccia.

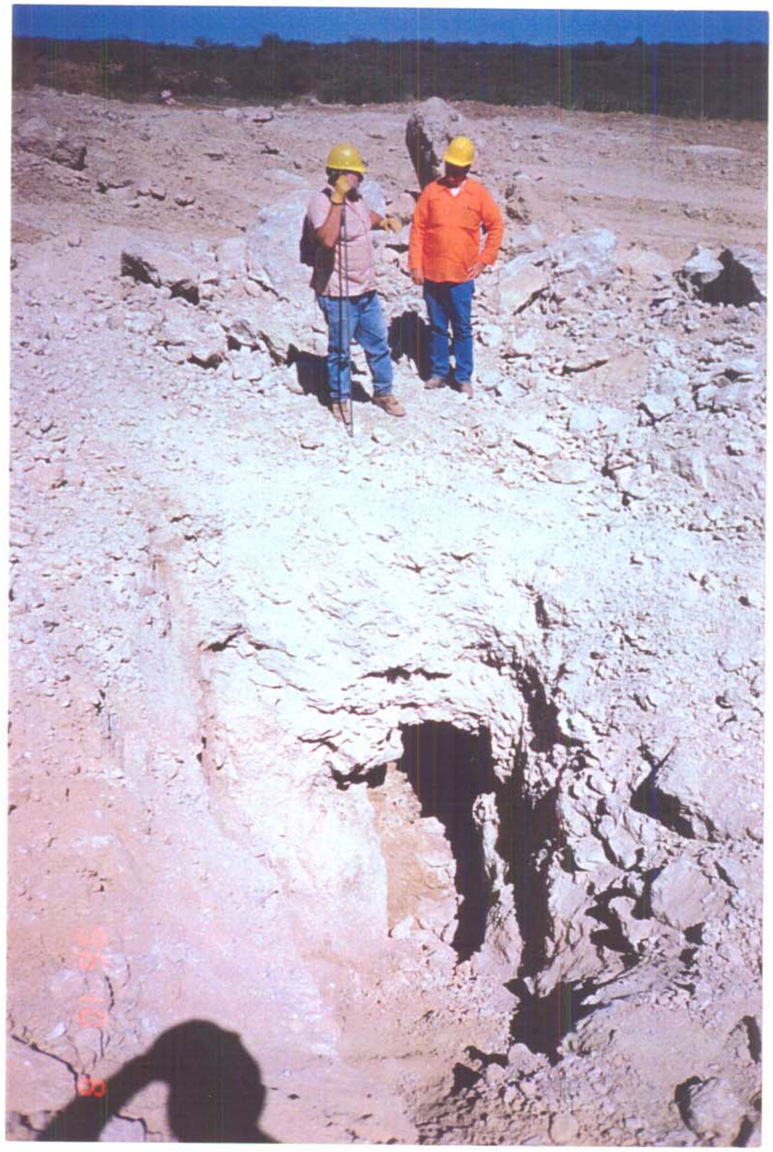


Figure 2 Cave area collapsed by D-9 dozer.

Travertine: The travertine is distinctively banded with alternating layers of white to cream color, and red brown to brown and tan colored layers. Within the red color-banded zones, a lime green calcite is also found. The red colored beds are believed to be caused by oxidized hematite taken into calcite crystal structure during their formation. The white and tan bands of the travertine range in thickness from less than one-half inch to several inches. The unit is composed of the spring-deposited mineral calcite with grain size ranging from fine to coarse crystalline. The travertine ranges from soft to hard. The travertine contains numerous voids, ranging in size from vugs that are less than an inch across, to caves greater than ten feet in diameter.

Where exposed, the travertine banding is horizontal to gently folded, and locally dips forming relatively small anticlines, synclines, and kink folds. The travertine is massive, poorly jointed, and moderately thick. The unit is known to be at least 50 feet thick based on test drilling data, but may be as much as 100 feet thick. The unit outcrops locally in Mayer, covering less than about ¼-square mile. Although the unit is not located on any of the available geologic maps due to the scale of the maps, it is believed to be a member of the Tertiary-aged Hickey Formation, which is also mapped in the vicinity of the study area (Anderson and Blacet, 1972 a&b).

Breccia: The unit is a light gray to dark gray, soft and massive matrix supported breccia. The breccia is poorly to moderately cemented with calcite. It is composed primarily of subangular to angular clasts of metamorphic rock fragments cemented in a matrix of angular sand. The rock fragments range from ½-inch to 12 inches in diameter. The breccia is generally not well exposed in outcrops within and adjacent to the study ar Composed of gravelly to bouldery clasts of igneous and metamorphic rock in a sandy matrix. The alluvial fane deposits were observed to be only weakly to moderately caliche cemented at the surface. Strongly caliche cemented materials could be encountered at depth, particularly near the bedrock/alluvium boundary. ea. The breccia was encountered above and below the travertine in exploratory drill holes along portions of the alignment (AGRA, 1993). The breccia was also exposed in debris created by portions of the excavation where blasting was done. No void features appeared to have been developed in the breccia.

Karst Features Identified Along Roadway Alignment

Throughout the project and adjacent areas that are underlain by travertine, only one surface expression of a karst feature was known to exist prior to the highway realignment construction. This surface expression of a karst feature was a small cave entrance, located along the shoulder of the original southbound lanes of SR 69 at about station 3702+00. The cave opening was large enough for three spelunkers to enter the cave and to survey its passageways. The approximate location of the "Mayer Mystery Cave" is depicted on Figure 1.

Exploration drilling conducted by as part of the highway alignment design investigation encountered reportedly small voids. ADOT also conducted drill hole exploration during October 1994. The purpose of the ADOT program was an attempt to determine the extent of voids in the vicinity of the "Mayer Mystery Cave". Logs of both auger and core borings reported voids with open intervals ranging from at least one foot to eight feet. The top of the voids range from about 3 to 40 feet below existing grade.

Field Investigation

Geophysical surveys, along the SR 69 realignment section, were conducted in two phases. Phase I concentrated on the southbound lanes segments, including the southbound shoulder area and a portion of the median. Phase II concentrated on the northbound lanes segments including the remainder of the median and the northbound lanes shoulder. The field work for Phase I and II, was performed from October 29, 1996 to November 1, 1996 and from June 26, 1997 through July 3, 1997, respectively.

Geological/Geophysical Model

During a GPR survey, repetitive, short duration (a few nanoseconds) electromagnetic pulses are radiated into the earth from a broad-bandwidth antenna placed on the ground surface. Pulses are partially reflected back to the antenna by dielectric discontinuities in the subsurface. Dielectric contrasts can be caused by changes in moisture content, stratigraphy, man-made objects, or voids within a limestone.

Strata changes within the limestones may produce semi-continuous radar reflections that change over tens to hundreds of feet on the data

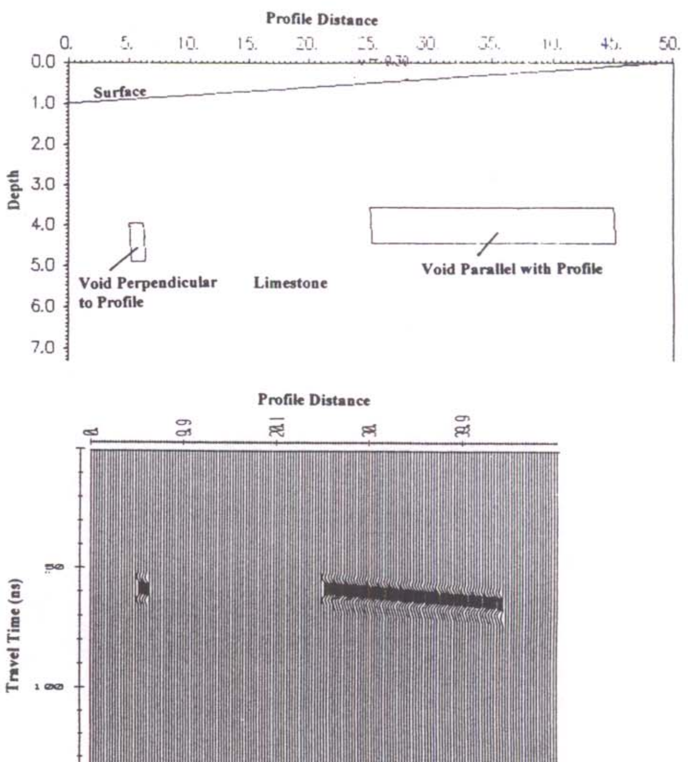


Figure 3 Theoretical radar data of subsurface void.

caused by a void will change according to the void's geometry and the orientation of the data profile over the void. Figure 3 shows the theoretical anomaly associated with a narrow, long axis void (Sensors and Software, 1995). The left of the plot shows the characteristic hyperbolic shape anomaly over a void with its long dimension perpendicular to the data profile and is also valid for a semi-spherical anomaly with no long axis. The right side of the plot shows a long anomaly with a large amplitude top and bottom representing the void/limestone contact when the profile is subparallel with the void's long axis.

The GPR method is the most appropriate surface geophysical method to use to locate voids at this site. The method has the highest subsurface object resolution of any method because very high frequency (narrower pulse width) signals are used to probe the subsurface. The major limitation of radar is its ability to penetrate conductive soils, such as saturated alluvium and clays. These conditions do not exist at the site. The data were collected either directly on the dry limestone or on a thin layer of gravelly fill on top of the dry limestone.

GPR Survey Design

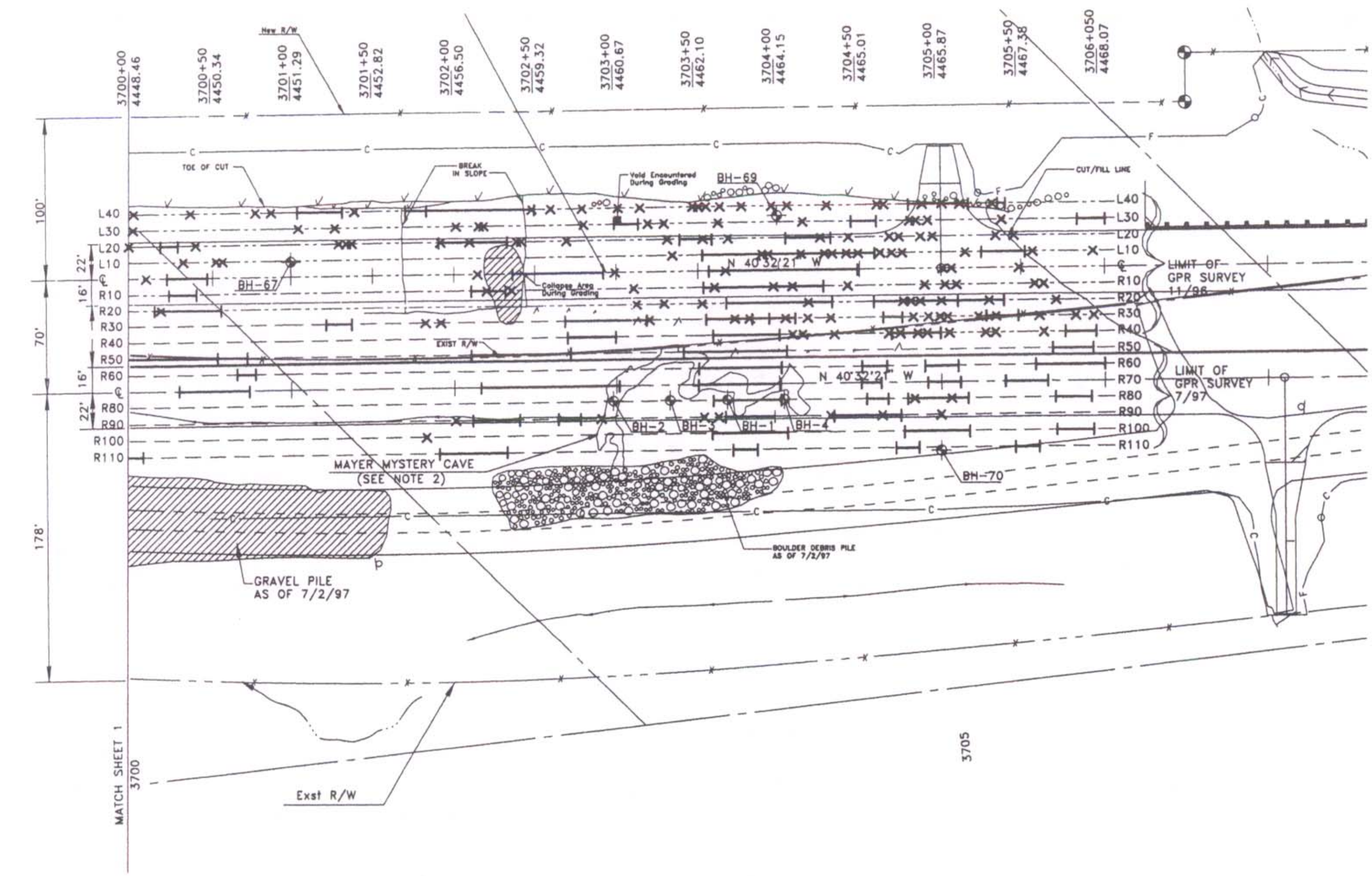
The radar survey was designed to detect voids within the upper 30 feet that could collapse and expose the traveling public to potential hazards along the roadway. The smallest void of interest was estimated to be a cube two feet on each side. Collapse of smaller dimension voids would probably not seriously effect the roadway. The GPR measurement parameters were chosen to detect voids with a vertical dimension larger than two feet (Figure 4).

Figure 4 GPR antenna/receiver collecting data along profile line

The measurement profile geometry was also designed to detect voids with spacial dimensions larger than two feet. A grid of parallel profiles were constructed along the roadway axis from Station 3698+00 to 3706+00 (Figure 5). The profiles extended from the south shoulder of the southbound lanes about 150 feet to the northern shoulder of the northbound lanes. Adjacent profiles were 10 feet apart. Sixteen parallel transects were continuously surveyed producing a total of almost 14,000 lineal feet of GPR profiles. Data were collected with the 100 MHZ antenna that has a beam width at depth about four feet on each side of the profile. Therefore, this antenna should be able to detect a void even if it has a four feet perpendicular offset from the profile. Each profile probed a data swath eight feet wide (four feet on each side of the centerline) resulting in a 2-foot wide zone between two adjacent profiles that was covered by the surveys. Data were collected at two foot intervals along each profile which should be adequate to detect a two foot cube.

GPR Survey Results

The processed sections for Profiles L40, L30, L20, L10, southbound centerline, and R 10 through R110 were analyzed individually. Large-amplitude anomalies appearing in the lower part (longer travel times) of the section were identified as possibly being air-wave reflections from nearby surface features. When possible these correlations were made and those anomalies ignored as possibly representing voids. Candidate anomalies were highlighted along the bottom of the sections (Figure 6) On the southbound lanes, 209 possible void anomalies were interpreted and 257 anomalies on the northbound lanes.



SUMMARY NOTES:

1. Drawing Modifed From Plan Sheet STA 3700+00 to 3705+00; Big Bug Bridge #1 to #4; SR 69; Sheet 14 of 15; Prepared by Sverdrup Corporation 9/94.
2. Mayer Mystery Cave, Taken From Map Location Prepared By Bill Rodgers, Andy Yednak & Bill Lowell-Britt, 12/21/93.

EXPLANATION:

- ■ Blast Hole Location (Data Provided by C.S. McCrossan Inc. 11/96)
- GPR Survey Line (Southbound Lane)
- GPR Survey Line (North Bound Lane Survey)
- Bore Hole Location (BH-1 to BH-6 Data Provided by A.D.O.T.)
- Bore Hole Location (BH-67, BH-69 & BH-70 Data Provided by AGRA Earth & Environmental Group)
- GPR Linear Anomaly
- × GPR Anomaly

Figure 5 GPR Profile line location plan showing approximate site of "Mayer Mystery Cave" and GPR anomalies.

Finally, all sections were compared and the candidate anomalies screened to determine the ones most likely to represent voids. Interpreted voids' location, depth and orientation are depicted on the anomaly plan map (Figure 5)and cross sections (Figure 7). Many individual anomalies identified on adjacent profiles were grouped together to form large dimension anomalies or zones containing many small dimension anomalies that could represent interconnected voids

Void Verification and Remediation

Southbound Lanes

Anomaly Verification Program: The anomaly verification program involved the test drilling of selected areas based on the results of the GPR survey conducted along the future southbound lanes of the SR 69 realignment. The GPR survey located 51 target areas where subsurface voids were interpreted to be present. The target areas were drilled using an air track drill (Figures 8). If a suspect anomaly was confirmed as a void additional test holes were drilled around the initial drill hole on five foot centers to determine the void limit. All of the test holes (for the southbound lane) were drilled to a depth of 46' below grade. A total of 191 test holes were drilled.

During the drilling operation, voids were encountered at most of the identified anomaly locations. When voids were intersected, the drilling response was dramatic with the loss of air circulation and drop of the drill rod. The anomaly site was drilled first and, if the voids' presence was confirmed, additional bores were drill in a pattern away from the initial bore to 'chase' the void in an attempt to determine it's lateral extent. The depth to the top of the voids ranged from as shallow as four (4) feet to as deep as 40 feet below existing grade. The open intervals (top to bottom) of the voids encountered by the drilling are estimated to ranged from one-foot to at least 26 feet with lateral dimensions estimated to range from less than 5 feet to as great as 60 feet. The areas that appeared to exhibit the most critical void features are depicted on Figure 9 which also depict the GPR survey lines, GPR anomalies identified from the process geophysical data, drill holes that encountered voids, and drill holes that did not encounter voids.

Void Remediation Program: The void remediation program was conducted during January and February, 1997 by the contractor to prepare a stable subgrade. The program involved the southbound lanes of SR 69 between station 3698+00 and station 3706+00, including portions of the median and shoulder. As directed by ADOT, void remediation was limited to the depth of about 20 feet below subgrade elevations. Although voids were encountered below 20 feet, it was ADOT's opinion that remediation of the upper 20 feet would effectively bridge the lower voids. The void remediation program activities were monitored and documented by Geological Consultants Inc.

This phase of work included the drilling out (defining) of void areas which were initially characterized during the anomaly verification test drilling program (Figure 10). Once a void area was defined, it was then selected for either blasting or grouting at the direction of ADOT. Three void areas were shot during this period of work to remove the void roof. Areas opened by blasting were further mitigated by removing all of the blast debris and backfilling the open void with a controlled fill. A geogrid type filter fabric was installed prior to backfilling to prevent piping of fine grain sediments into deeper voids. As directed by ADOT, some of the smaller void areas were not shot. Void areas not shot were filled to the fullest possible level using a sand-cement grout.

Northbound Lanes

Anomaly Verification Program: Because of the high degree of success with the cave anomaly/verification program experienced in the south bound lanes phase of the project, the anomaly verification test drilling program was not conducted along the northbound lanes. The locations of the GPR Survey anomalies were used as the basis to proceed directly with the void remediation program.

Void Remediation Program: The void remediation program was conducted by the contractor during July and August, 1997. The drilling program to delineate void areas was conducted between station 3697+50 and station 3706+00, including portions of the median and shoulder. Interpretation of the GPR data identified 173 anomalies within the north bound lanes suspected to be voids from the surface to a depth of about 40 feet. Anomalies within 20 feet of the surface were drilled, and the location and depth to voids encountered, as well as the size of the void, were

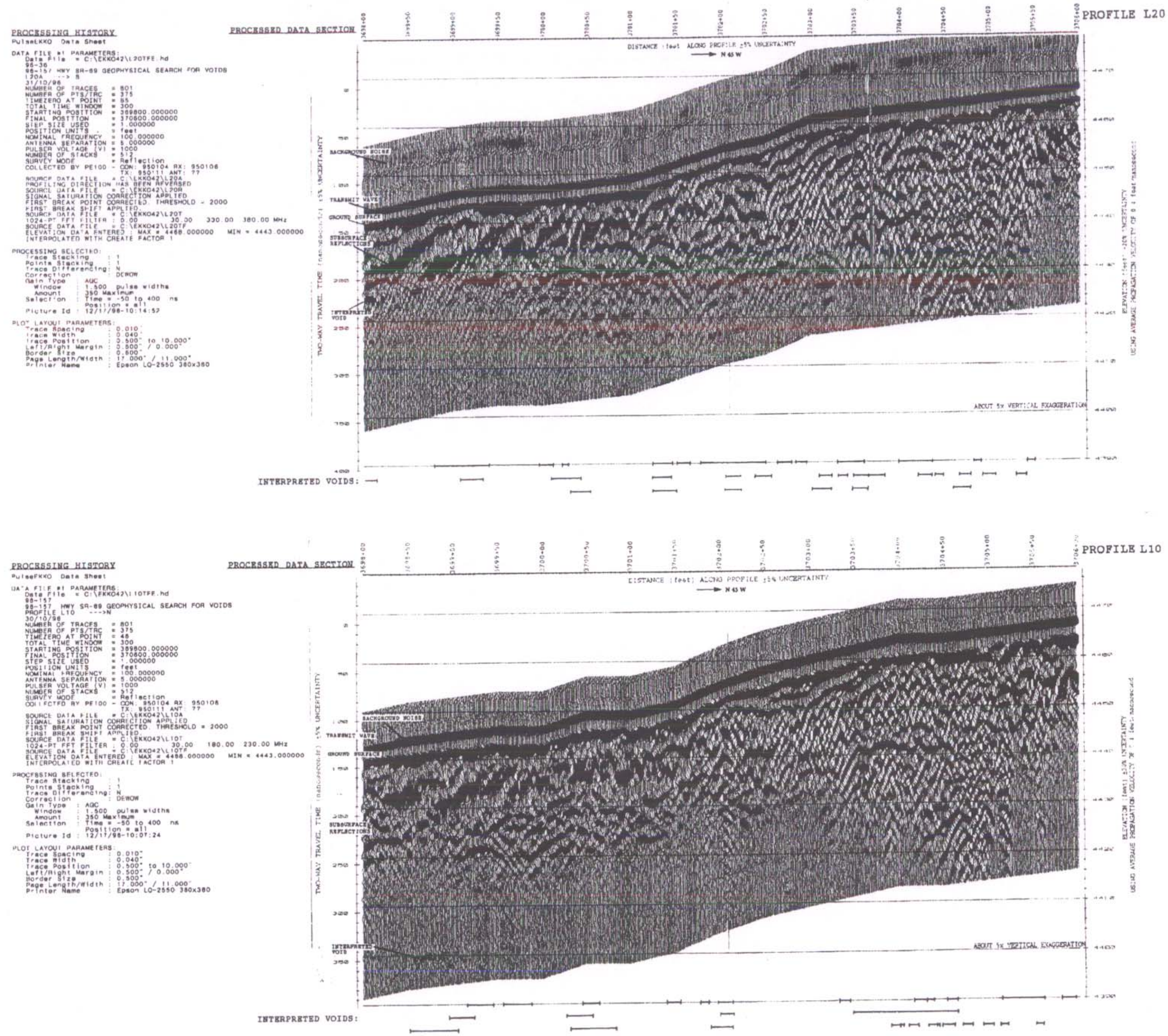


Figure 6 Typical GPR data profiles collected along cave-affected alignment section

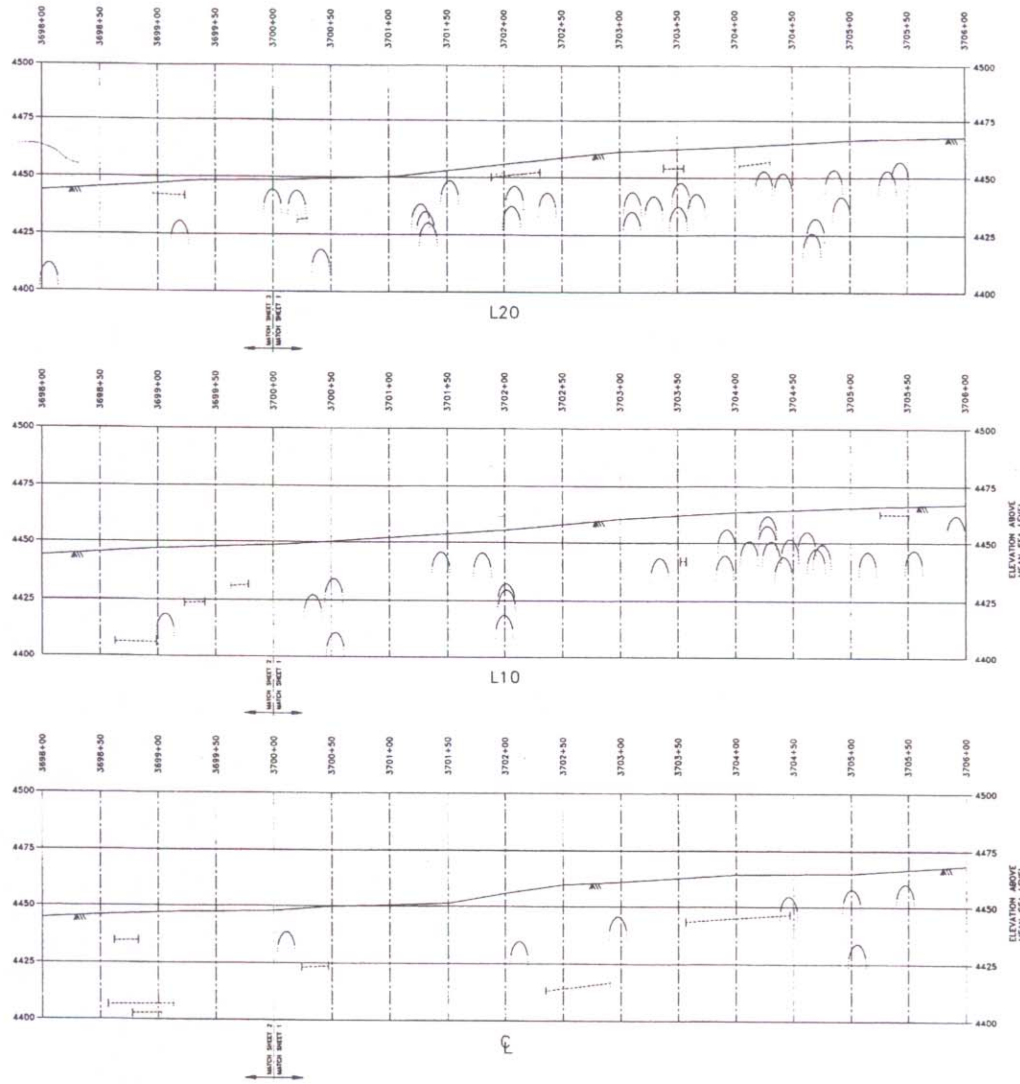


Figure 7 Profiles along cave-affected section of alignment depicting interpreted GPR anomalies. Hyperbola indicates individual anomaly; bracketed, dashed line indicates linear anomaly.

documented in the field by Geological Consultants Inc. This drilling process continued until void areas were defined and surrounded by drill holes in which no voids were encountered. Once a void area had been defined, a remediation method of either blasting and backfill or grouting of the void was implemented.

Twenty-four of the GPR anomalies were confirmed as voids during drilling within the upper 20 feet of the section. Voids encountered during the drilling of the geophysical anomalies in most cases were interconnected with adjacent voids. Nine large void areas were defined by a combination of drilling GPR anomaly sites and chasing the voids to their limit. Three of the caves were remediated by blasting and backfilling with the remainder closed by grouting.

SUMMARY

GPR surveys were conducted along a portion of the SR 69 highway realignment between stations 3698+00 to 3706+00 where known karst features had been previously documented and which were known to be in very close proximity to proposed roadway grades. The survey included both the northbound and southbound lanes, their respective shoulders and the median between the lanes.

Figure 8 Air track drill used for anomaly verification along south bound lanes segment.

The GPR survey detected subsurface anomalies that were interpreted as voids and many were confirmed by subsequent drilling. This survey proved a rapid method to statistically characterize the travertine (onyx) formation in which the voids were found and focus remediation to locations where it was deemed needed. The GPR survey collected data almost continuously along 16 profiles spaced 10 feet apart and oriented parallel to the roadway centerline. Measurement parameters were designed to resolve voids larger than a cube, two feet on a side, within the upper 30 feet. Data was extensively processed to produce sections emphasizing anomalous areas. A theoretical model was constructed for different void shapes and shows the corresponding anomalies shapes. These models were used as a guide to identify anomalies within the data sections that could represent voids.

Numerous irregularly-shaped voids of small (± 2 feet in diameter) to large (greater than 20 feet in diameter) were interpreted in a zone that extends from 3 to 40 feet below roadway grades. Remediation efforts were concentrated within the upper 20 feet of the section in an effort to form a reasonably stable platform to "bridge" the known lower voids. Remediation in the upper 20 feet of the roadway section included the opening of large near surface voids by blasting followed by their subsequent backfill with an engineered fill. Smaller void areas were filled with a standard grout mix.

Three monitoring points have been established adjacent to the void-affected, remediated roadway. These points can be used by ADOT to monitor the performance of the highway and its response to void remediation.

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Figure 10.1 (Top) Shot hole pattern for shot designed to collapse roof of near-surface cave structure; (Bottom) Cave roof collapsed by blasting.

Figure 10.2 (c) Final remediation of collapsed cave structure with select backfill.